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Numerical Modeling and Performance of Two Test Embankments Based on Surcharge Preloading, PVDs and Vacuum: *Drain-to-Drain* and Airtight Membrane

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Abstract. The soft soils, characterized by their high water content, high compressibility, low resistance to shear and low permeability, need to be stabilized before the construction of the buildings they will support. The purpose of this stabilization is to prevent differential settlements and/or unacceptable collapses in buildings that can affect their operation or endanger the safety of the structures or the people who inhabit them. A simple preload system with vertical drains is an option for the stabilization of soft soils. This technique usually consists of representing the weight of a structure by means of an embankment of earth material and complementing it with vertical drains to induce settlement in a shorter time. Another option to generate a preload in the soil is through the application of vacuum pressure in the surface layers. The vacuum pressure is transmitted to the ground through prefabricated vertical drains (PVDs) by two techniques: *drain-to-drain* or with an airtight membrane. In this paper, the behavior of two test embankments built in the area of the former Lake Texcoco (where the construction of a new airport was planned) with a preload solution combined with PVDs and vacuum consolidation using *drain-to-drain* and airtight membrane technologies is studied using numerical modeling and field instrumentation.

Keywords. Soil improvement, vacuum preloading, drain-to-drain, airtight membrane.

1. Introduction

Vacuum consolidation is a soil preloading technique in which the maximum pressure that can be applied corresponds to the atmospheric pressure of the site. It is also called *vacuum preloading* because it can be equivalent to a simple preload of earth material 3 to 4 m high (depending on the material and subsoil characteristics). In general, there are two technologies for the application of vacuum in a soil: a) *drain-to-drain* and b) *airtight membrane* [1] [2].

In the *drain-to-drain* technique, vacuum is applied directly through flexible horizontal pipes immersed in a layer of permeable material placed on the natural ground.

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The horizontal pipes, in turn, are connected to the vertical prefabricated drains (PVDs) that can transmit the vacuum to the surface layers of the ground. The effect of the vacuum is to induce soil consolidation by reducing the pore pressure, and consequently increasing the effective stress by an equivalent magnitude, when the total stress does not change [3].

In the *airtight membrane* technique, vacuum is created in an area that is confined under an airtight membrane. The vacuum is applied to horizontal drains immersed in a permeable material layer placed on the natural ground of the treated area. This layer is covered with an airtight membrane that is buried in the subsoil with help of a trench built around the periphery of the area improved, and this membrane is then covered with another layer of earth material. The system is complemented with prefabricated vertical drains (PVDs) that are not connected to the horizontal drains, but due to the confinement of the membrane, they receive the vacuum pressure and transmit it to the surface layers of the soil [4].

Traditional assessments in earth embankments (representing preload) assume 2D plane strain conditions, but consolidation around a vertical drain is an axisymmetric problem. Thus, the conventional finite element method (FEM) in the 2D plane strain cannot be applied directly, since it is not representative of the conditions of the preloading-PVDs systems [5]. Some theories proposed since 1980 have helped to simplify these analyses, establishing appropriate equivalent properties between the axisymmetry and plane strain state [6] [7] [8] [9] [10] [11]. These theories are based on the properties of the subsoil to be improved, the efficiency of the vertical drains (geometry, discharge capacity, smear effect, and drainage conditions) and the type of preload used (simple or with vacuum).

This paper emphasizes the numerical evaluation of the settlements in two test embankments with preloading, PVDs and vacuum application with the techniques: a) *drain-to-drain* and b) *an airtight membrane*. Calculations are performed using numerical modeling with finite elements in 2D plane strain state, considering the theories that allow equivalence between the axisymmetry and 2D plane strain state. The modeling results are compared with field records. In addition, the degree of consolidation (DOC) achieved with each vacuum technique is determined considering the field measurements in settlement plates located at the center of both test embankments. In the end, the conclusions of the evaluations carried out are provided.

2. Description of the study site

The evaluated test embankments are located at the site where the construction of the New Mexico City International Airport (NAICM, in Spanish abbreviation) was planned, the lowest portion of the Basin of Mexico that was previously occupied by the Lake Texcoco (State of Mexico, Mexico). The former Lake Texcoco was the largest and shallowest lake in the basin. The groundwater in the area is characterized by its high salinity (up to 10 g/l) and alkalinity (more than 10 meq/l) [12, 13]. The soils of Texcoco consist of thick layers of soft clay of lacustrine origin with microfossils (benthic diatoms and epiphytes) interspersed in volcanic sediments [14].

The stratigraphy of the site corresponds to the typical Lacustrine Zone, according to the Geotechnical Zoning of Mexico City [15]. The main layers of the soil are [12]: a) Surface Crust (SC) formed by a mixture of clay with sand, in some areas with cracks; b) Upper Clayey Formation (UCF), a thick layer of highly compressible lacustrine clay interspersed with seams of volcanic origin; c) Hard Layer (HL), composed of sand and silt with variable cementation; d) Lower Clayey Formation (LCF), of the same origin as the UCF but differing by its lower water content and compressibility; e) Deep Deposits (DD), formed by silt and sand interspersed with hard clays; f) Deep Clayey Formation (DCF), a third layer of clay with similar characteristics to the others; and g) Deep Stratified Formation (DSF), composed of stratified deposits of clay, sand and silty sand [16] [17]. At the site, the groundwater table (GWT) varies between 0.5 and 1.0 m in depth (depending on the wet or dry seasons).

3. Characteristics of the test embankments

The test embankment for the application of *drain-to-drain* vacuum (Figure 1) has a rectangular shape in plan view, with dimensions of 50 × 70 m in the crown (3,500 m^2 area) and 56 × 76 m in the base, with a slope of 1.5:1. The system consists of a preload of volcanic igneous rock called *tezontle* with a height of 2 m, placed in four layers (equivalent to a load of 22.5 kN/m^2). The system has 3,045 cylindrical prefabricated vertical drains (PVDs of a star-type cross-section, named *star drain*, wrapped in a nonwoven geotextile) placed in a triangular arrangement with a separation of 1.2 × 1.2 m at a depth of 28 m from the natural ground level (NGL).

The PVDs are connected directly to vacuum pumps through flexible horizontal pipes (Figure 2a). The vacuum system consists of six pumps, all placed on the south side of the embankment. Ten drain lines are connected to each pump, and each line has 50 or 51 drains, making a total of 500 to 508 drains per pump. The average vacuum pressure applied to the test embankment was -58 kPa.

Figure 1. Test embankments with simple preload, PVDs and vacuum: (a) *drain-to-drain* and (b) with an airtight membrane at the NAICM site (photo courtesy of E. Botero, 2018).

The trial embankment with the vacuum application by means of an *airtight membrane* has the same geometry in plan view as the *drain-to-drain* section (Figure 1). The test section has a 2-m-high *tezontle* preload, placed in four layers (equivalent to a load of 27.1 kN/m^2), with a total of 2,808 prefabricated vertical drains (of a band-type cross-section, named *wick drain*, wrapped in a nonwoven geotextile), placed in a triangular arrangement with a separation of 1.2 × 1.2 m at a depth of 27 m from the NGL. The geomembrane (Figure 2b) was placed when the *tezontle* preload was 1 m high from the NGL and anchored into a trench filled with bentonite around the embankment base to ensure the tightness of the system (Figure 2b). Subsequently, the membrane was covered with layers of *tezontle* until reaching 2 m in height. The average vacuum pressure applied to the system was -63 kPa.

In both test embankments, the vacuum was applied for six months. Each test lasted one year, including the construction stage, the vacuum application and a two-month observation period after the vacuum pumps were turned off.

(a) *Drain-to-drain* technology
(Start: June 26, 2016 - End: June 12, 2017)

(b) Airtight membrane technology
(Start: May 10, 2017 - End: May 7, 2018)

Figure 2. Test embankments: (a) photo courtesy of PIMOSA (2017) and (b) photo courtesy of MENARD (2018).

4. Numerical modeling

4.1 General considerations

According to the index, mechanical and hydraulic properties provided in Tables 1 and 2, it is observed that the Upper Clayey Formation 1 (UCF 1) has considerable overconsolidation ratios OCR=2.7 (embankment area with *drain-to-drain* vacuum) and OCR=2.5 (embankment area with airtight membrane). The Upper Clayey Formations 2 to 4 (UCF 2 to UCF 4) and Lower Clayey Formation (LCF) are characterized as soft highly compressible materials and are usually found as consolidated to slightly overconsolidated. Based on the characteristics described above, these layers are represented by the *Soft Soil* model. Materials such as the Surface Crust, Hard Layer and Deep Deposits, which are characterized by some content of silt or sand and having a higher resistance to shear strength, are represented by the *Mohr-Coulomb* model.

The evolution of the consolidation process of a soil with a preload system, vertical drains and vacuum can be studied by means of numerical modeling in a three-dimensional form (3D) or in a plane strain state (2D). As a first option, a 3D analysis directly represents the phenomenon of radial consolidation; however, it may require special computing equipment and a considerable calculation time. Another technique of modeling this type of system in a simpler way and obtaining similar results to a 3D model is by establishing equivalent properties of geometry or permeability [18] [19] in a plane strain state. In this paper, 2D numerical models were used to study the evolution of the consolidation in trial embankments with vacuum by the *drain-to-drain* and airtight membrane techniques. Both models were restricted sideways, by approximately twice the width of the preload embankment (56 m), to reduce the influence of the stress bulb generated by the load transmitted by the embankment, resulting in a discretized medium 180 m long and 50 m deep. The settlement calculations for both systems were carried out with numerical models by means of the FEM in the PLAXIS 2D 2017 code, considering equivalent permeability properties based on the theories of Indraratna and Redana [10] and Indraratna et al. [11]. Finite element meshes were generated considering triangular elements of 15 nodes with 12-point Gaussian integration. In total, the mesh of the *drain-to-drain* model includes 12,440 elements and 99,969 nodes, while the airtight membrane model has 12,070 elements and 97,097 nodes.

Table 1. Geotechnical model of soil properties in the embankment with the *drain-to-drain* technique.

Layer	Depth, m		γ	ν'	e_0	C_r	C_c	OCR	c_u	c	ϕ'	K_0	k_h
	from	to	kN/m^3						kPa	kPa	°		m/day
SC	0.0	1.0	15.0	0.33	-----	-----	-----	-----	----	100	40	0.36	4.3×10^{-01}
UCF 1	1.0	5.4	12.0	0.3	3.64	0.25	1.17	2.7	17	0	40	0.68	5.6×10^{-04}
UCF 2a	5.4	9.7	11.4	0.3	4.74	0.27	3.19	1.2	15	0	40	0.40	3.5×10^{-04}
Seam 1	9.7	10.3	15.0	0.33	-----	-----	-----	-----	----	40	35	0.43	-----
UCF 2b	10.3	12.6	11.4	0.3	4.74	0.27	3.19	1.2	15	0	40	0.40	3.5×10^{-04}
UCF 3a	12.6	14.6	11.0	0.3	3.73	0.21	4.59	1.3	27	0	40	0.42	2.0×10^{-04}
Seam 2	14.6	15.2	15.0	0.33	-----	-----	-----	-----	----	40	35	0.43	-----
UCF 3b	15.2	25.4	11.0	0.3	3.73	0.21	4.59	1.3	27	0	40	0.42	2.0×10^{-04}
Seam 3	25.4	26.0	15.0	0.33	-----	-----	-----	-----	----	40	35	0.43	-----
UCF 3c	26.0	30.6	11.5	0.3	3.73	0.21	4.59	1.3	27	0	40	0.42	2.0×10^{-04}
HL	30.6	32.6	18.0	0.33	-----	-----	-----	-----	----	50	45	0.29	1.1×10^{-03}
LCF	32.6	43.8	13.0	0.3	4.28	0.29	2.65	1.0	49	0	40	0.36	1.5×10^{-04}
DD	43.8	50.0	19.0	0.33	-----	-----	-----	-----	----	50	45	0.29	2.9×10^{-03}

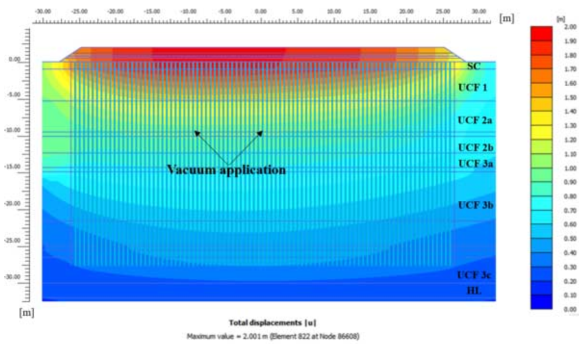
Table 2. Geotechnical model of soil properties in the embankment with the *airtight membrane* technique.

Layer	Depth, m		γ	ν'	e_0	C_r	C_c	OCR	c_u	c	ϕ'	K_0	k_h
	from	to	kN/m^3						kPa	kPa	°		m/day
SC	0.00	0.70	15.0	0.33	-----	-----	-----	------	------	100	40	0.36	4.3×10^{-01}
UCF 1	0.70	4.50	12.7	0.3	3.64	0.25	1.17	2.5	16	0	40	0.64	2.4×10^{-03}
UCF 2a	4.50	9.00	11.7	0.3	8.84	0.19	1.97	1.7	17	0	40	0.50	9.3×10^{-04}
Seam 1	9.00	9.50	15.0	0.33	-----	-----	-----	------	------	40	35	0.43	------
UCF 2b	9.50	13.50	11.2	0.3	9.99	0.16	1.64	1.6	20	0	40	0.48	9.3×10^{-04}
UCF 3a	13.50	17.30	12.5	0.3	6.14	0.03	1.01	1.7	30	0	40	0.50	6.8×10^{-04}
UCF 3b	17.30	22.50	12.2	0.3	7.49	0.08	1.15	1.4	26	0	40	0.44	6.8×10^{-04}
Seam 2	22.50	23.00	15.0	0.33	-----	-----	-----	------	------	40	35	0.43	------
UCF 3c	23.00	24.00	12.2	0.3	7.49	0.08	1.15	1.4	26	0	40	0.44	5.0×10^{-04}
Seam 3	24.00	24.50	15.0	0.33	-----	-----	-----	------	------	40	35	0.43	------
UCF 4	24.50	30.15	12.2	0.3	7.99	0.13	1.30	1.4	35	0	40	0.44	7.0×10^{-04}
HL	30.20	31.20	18.0	0.33	-----	-----	-----	------	------	50	45	0.29	1.1×10^{-03}
LCF	31.2	44.0	13	0.3	4.28	0.29	2.65	1.0	49	0	40	0.36	1.5×10^{-04}
DD	44.0	50.0	19	0.33	-----	-----	-----	-----	----	50	45	0.29	2.9×10^{-03}

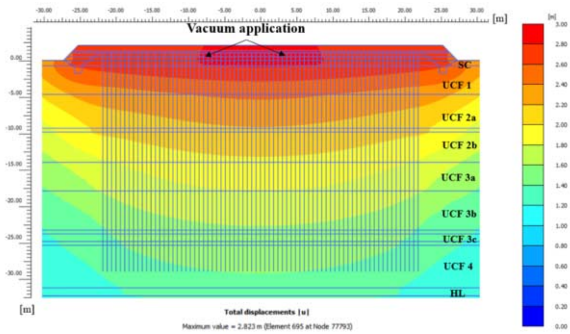
4.2 Assessment of settlements

The settlements to the center of the embankments obtained by numerical modeling with the previous considerations at the end of the vacuum application (6 months) showed s=200.01 cm for the model with the *drain-to-drain* vacuum (Figure 3a) and s=282.3 cm for the model with vacuum with the airtight membrane (Figure 3b).

Figure 4 shows a comparison of the settlements numerically calculated with the field records in the settlement plates located at the center of each test platform. The numerical modeling with assumed equivalences provides results that are almost coincident with the field measurements. Similarly, in this figure it is noticeable that after turning off the vacuum pumps, the ground continues to settle during the following months, but with a lower settlement rate in the case of the *drain-to-drain* section. In the case of the section with the airtight membrane, because the valves that connect the horizontal drains with the vacuum pumps remained closed, for 15 extra days after turning off the vacuum, the settlements continued to increase in this vacuum dissipation period (approximately 5 cm); however, once the valves were opened (day 316), a sudden recovery (expansion) of the accumulated settlement is noticeable.



a) *Drain-to-drain* technology (2D model)



b) Airtight membrane technology (2D model)

Figure 3. Settlements obtained at the end of the vacuum application in the evaluated test sections.

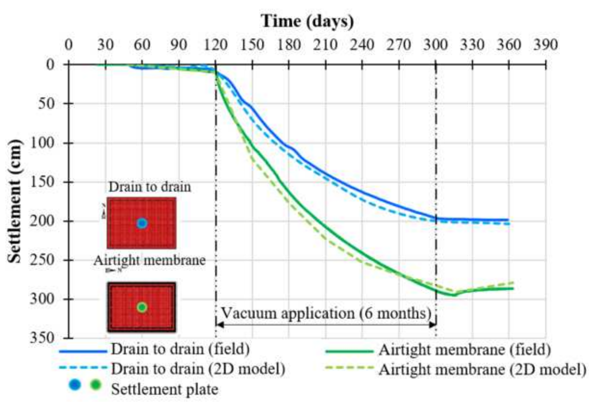


Figure 4. Evolution of settlements in the central part of the embankments with vacuum: field records vs. numerical modeling.

4.3 Estimation of the degree of consolidation

To find the efficiency of each vacuum improvement technique, the achieved degree of consolidation (DOC) was estimated. For the previous cases, the final settlements were determined by primary consolidation, considering the field measurements in the settlement plates at the center of each test embankment. The estimated ultimate primary settlement with the Asaoka's method [20] to the center of the embankment with the *drain-to-drain* vacuum is s_{ult} = 223.37 cm, and in the embankment with the *airtight membrane* s_{ult} = 330.7 cm, as shown in Figures 5a and 5b, respectively. From the ultimate primary settlements previously obtained, the degree of consolidation was estimated by the following expression [21]:

$$U = \frac{s}{s_{ult}} \tag{1}$$

where s is the consolidation settlement $s_1, s_2 ..., s_n$ at a consolidation time $t_1, t_2, ..., t_n$ (in this study, the measured settlement when the vacuum application stops) and s_{ult} is the ultimate primary settlement (when the excess pore water pressure has completely dissipated).

Based on the above, the degree of consolidation that was obtained in the embankment area with the *drain-to-drain* vacuum is U= 88.26%, and that in the embankment with the *airtight membrane* is U= 87.63%.

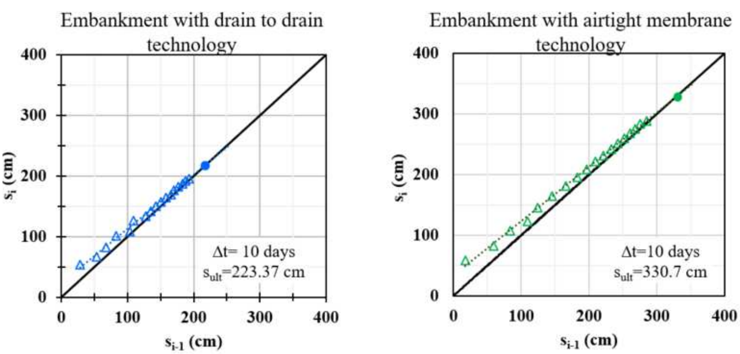


Figure 5. Estimation of the ultimate primary settlement s_{ult} at the center of each test embankment.

5. Conclusions

The vacuum preloading system (*drain-to-drain* or with an *airtight membrane*) combined with vertical drains is a soft soil improvement technique that helps accelerate the progress of settlement by primary consolidation and decrease the long-term settlement (residual settlement). In this paper, the settlements of two test embankments that were built at the NAICM site in the former Lake Texcoco, with different vacuum application techniques: a) *drain-to-drain* and b) with an *airtight membrane*, were numerically estimated using the finite element method.

The use of the theories of Indraratna and Redana [10] and Indraratna et al. [11], which properly considered the equivalent properties of the soil to be improved using 2D numerical modeling, provided results for the settlements very similar to those measured in the field during the evaluated period of the embankments (one year). These theories present a great advantage in the reduction of the calculation time, since it has been demonstrated that the results of the 3D numerical analysis are practically the same as the 2D numerical results obtained with the theories of equivalence [19].

The two test embankments had similar characteristics in terms of the preload geometry and drainage level. The embankment with a *drain-to-drain* vacuum presented a lower settlement in relation to the technique with the *airtight membrane*; however, the consolidation degrees obtained with the two technologies were similar. This effect could be dependent on the vacuum pressure applied in each system and the subsoil compressibility properties of each improved site.

The numerical assessments carried out could be very useful for the prediction of settlements and vertical displacements that can be achieved by the soil improvement techniques, especially when time and cost restrict the construction and monitoring of large-scale test sections.

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